Combination of OFDM and spread spectrum for high data rate UWB: optimization of the spreading length

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***Abstract*— In this paper we investigate a new waveform based on Spread Spectrum Multi-Carrier Multiple Access (SS-MC-MA) for Ultra Wide Band (UWB) systems obtained by the combination of Orthogonal Frequency Division Multiplexing (OFDM) and Code Division Multiple Access (CDMA). This system is a great solution to combat frequency selectivity and narrowband interferers, and to manage the coexistence of several users and piconets. It also brings an interesting degree of freedom since the spreading codes of SS-MC-MA allow to optimize jointly the assignment of the number of used codes and the coding rates. We proposed methods to limit the Self-Interference (SI) between the spreading sequences by a judicious positioning of the subcarriers which carry spread data, and a selection of the spreading codes. The effect of the spreading code length is studied and shows that the code length has to be increased when the code rate gets higher to optimize the system performance. Through simulations it is demonstrated that the new UWB system outperforms the well known Multi-Band OFDM Alliance (MBOA) one.**

***Index Terms*— UWB, MB-OFDM, SS-MC-MA, spreading length optimization, self-interference.**

I. Introduction

Since the Federal Communications Commission (FCC) opened the frequency range from 3.1 GHz to 10.6 GHz for unlicensed operation of Ultra Wide Band (UWB) in 2002 [1], UWB has become a very attractive technology to create short range wireless communications with high data rates in a congested frequency sprectrum. As free spectrum access systems, UWB systems have to be designed not to disturb already existing narrowband systems such as Wireless Local Area Network (WLAN) 802.11a for example.

Since 2003, the standardization process of the Institute of Electrical and Electronics Engineers (IEEE) 802.15.3a task group, which aims at defining a high data rate physical layer for Wireless Personal Area Networks (WPAN), has seen the emergence and the confrontation of two main propositions. The first one is based on a pulse radio approach using a Direct Sequence Code Division Multiple Access (DS-CDMA) ternary codes and is supported by the UWB Forum. The second one follows a multi-carrier multi-band approach based on Orthogonal Frequency Division Multiplexing (OFDM) and is proposed by the Multi-Band OFDM Alliance (MBOA) consortium. The MBOA solution, supported by the main actors of the general public and component industries, seems to be a competitive solution by it's efficiency to cope with channel selectivity.

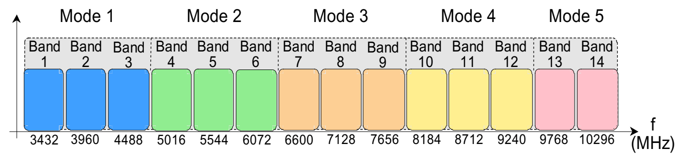


Fig. 1. Channels distribution for MBOA solution.

The aim of this paper is to propose a new system for UWB applications combining the multi-band OFDM approach with spread spectrum (SS). More precisely, we investigate the use of the so-called Spread Spectrum Multi-Carrier Multiple Access (SS-MC-MA) system for UWB applications. Particularly, it is highlighted that under a spreading length optimization, SS-MC-MA offers for the future WPAN good performance and great flexibility for the resource allocation between users of a same piconet. In that sense, section II briefly presents a critical analysis of the MBOA solution and points out the advantages of combining SS with multi-band OFDM in the UWB context. In section III, the principle of the new waveform for UWB is presented and a description of the related system is introduced as an evolution of the MBOA solution. Optimization parameters for the system are proposed to improve the performance of the proposed system in section IV. In section V, the results obtained with different spreading code length are presented and discussed. Finally, section VI concludes this paper.

II. The OFDM and CDMA combination interest

The MBOA consortium proposes to divide the available band into 14 sub-bands of 528 Mhz each, as illustrated in Fig. 1. The MBOA solution is described in detailed in [2] with the main parameters.

The MBOA solution offers some advantages for high data rate UWB applications, among which the signal robustness

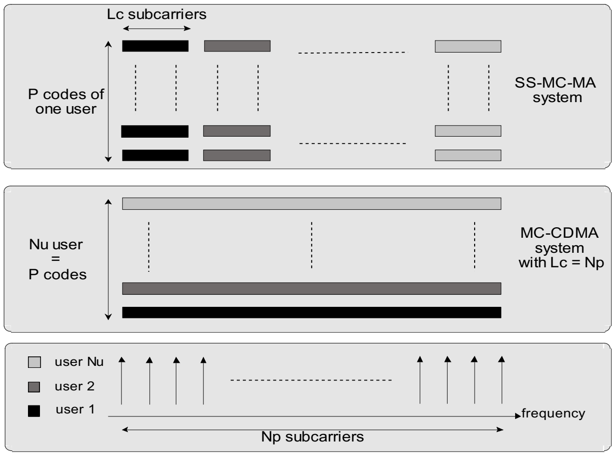


Fig. 2. Data distribution of different users for MC-CDMA and SS-MC-MA systems.

against the channel selectivity and the efficient exploitation of the signal energy received within the prefix duration. The main asset of the MBOA solution, as compared with the competitive impulsive radio solution, lies in its multi-carrier component which brings to the system a well recognized robustness to deep fades. The impulsive solution can actually hardly make use of all of the received energy, the number of the RAKE fingers being compulsorily limited for complexity reasons. However, the MBOA solution is relatively limited in a multi-user and multi-piconet context. Particularly, when the only three first sub-bands of the first mode are considered, conflicts immediately appear when a fourth user is added within a piconet, whereas scenarios going up to 6 simultaneous users have to be considered in practice.

To go beyond this limitation, recent studies have proposed to add a CDMA component to the MBOA solution in order to improve the system robustness or the resource sharing between several users [3]. This spreading component essentially allows to organize the access of several users to a common resource. Taking into account the UWB channel characteristics, frequency selectivity and slow time variations in an indoor environment, the spreading sequences are generally applied along the frequency axis, leading to the so-called Multi Carrier-CDMA (MC-CDMA) system. With MC-CDMA, the symbols of all users are transmitted by all the subcarriers as depicted in Fig. 2, the spreading code length L_c being lower or equal to the subcarrier number N_p of the OFDM multiplex. Compared to the "traditional" MBOA solution, and beyond a greater facility in the resource sharing, the MC-CDMA system also presents a better robustness against channel frequency selectivity and improves the UWB signal robustness against narrowband interferers ([3], [4]). This last point is fundamental for uncontrolled access to the spectral resource like UWB. In [3] however, authors suggest to use an MC-CDMA signal with a bandwidth B_w = 1.58 GHz, equivalent to 3 sub-bands of the MBOA signal, which leads to an highly increase of the sampling frequency of the analog-to-digital conversion.

In order to fully benefit from the advantages of the SS component, we have proposed in [5] an SS-MC-MA waveform, which is new for UWB applications and offers better performance and more flexibility in the resource management than MBOA as detailed in the sequel.

III. The SS-MC-MA based UWB system

A. SS-MC-MA principle

The SS-MC-MA scheme, illustrated in Fig. 2, consists in assigning to each user a specific set of subcarriers according to a Frequency Division Multiple Access (FDMA) approach. Code dimension L_c can then be exploited for an adaptive resource optimization and sharing (modulation type, data rate, ...). Spreading in the frequency domain yields a diversity gain and, like with MC-CDMA, improves the signal robustness against narrowband interferers. With an SS-MC-MA signal, symbols are transmitted simultaneously on a specific subset of subcarriers by the same user and undergo the same distortions. Self-interference (SI) which then replaces the Multiple Access Interference (MAI) obtained with MC-CDMA signals, can be easily compensated for using a single-user detection with only one complex coefficient per subcarrier.

B. System studied

The proposed system basically consists in an evolution of the MBOA system as depicted in Fig. 3. In this figure, the MBOA transmission chain is presented in continuous lines and the functions that are added to obtain the SS-MC-MA waveform are displayed using dashed lines. These functions are mainly the Hadamard Transform ("Fast Hadamard Transform": FHT) at the transmitter and the inverse transform (IFHT) at the receiver. In addition, Minimum Mean Square Error (MMSE) single user detection is applied. The spreading operation turns out to be simple, so the MBOA chain complexity is not significantly increased by the addition of the spreading component.

The main parameters of the SS-MC-MA system are listed in Table I. Walsh-Hadamard orthogonal spreading codes are used in this study to limit the SI and several spreading codes lengh L_c can be used. To compare performances of the SS-MC-MA system with different L_c, the number of useful subcarriers for MBOA is reduced from 100 to 96 for each OFDM symbol. This means that 4 additional guard subcarriers are added compared to the MBOA solution.

The SS-MC-MA signal waveform generated at the output of the IFFT expresses:

$$S(t) = \sum_{i=-\infty}^{+\infty} \sum_{n=-\frac{N_{\text{ST}}}{2}}^{\frac{N_{\text{ST}}}{2}} \sum_{l=1}^{P} D_l(i) c_{l,m} \times \Pi(t - iT_{\text{ZP}})\; e^{j2\pi n\Delta_{\text{F}}(t-iT_{\text{ZP}})} \tag{1}$$

where Δ_{F}, N_{ST} and T_{ZP} represent the subcarriers spacing, the total number of used subcarriers and the spacing between two consecutive OFDM symbols, respectively (Table I). $\Pi(t)$ is a rectangular window defined by:

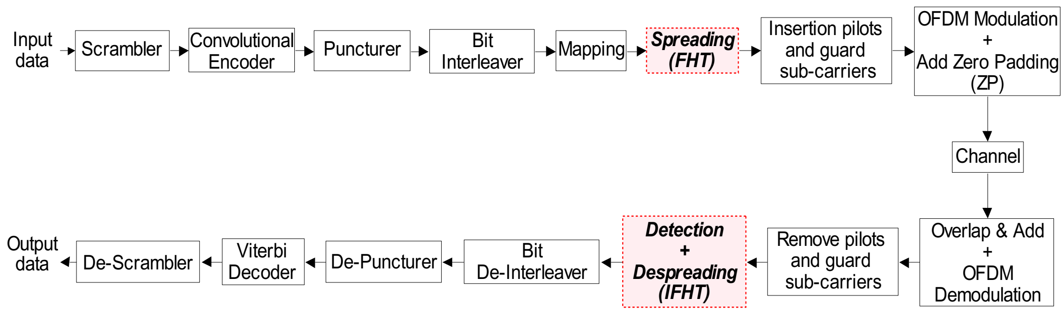


Fig. 3. MBOA transmission chain (SS-MC-MA in broken lines).

TABLE I
SS-MC-MA PARAMETERS

Parameter	Value
IFFT/FFT size	128
Sampling frequency	528 MHz
Transmission bandwith	490.87 MHz
N_{SD}: Number of data subcarriers	96
N_{SP}: Number of pilot subcarriers	12
N_{SG}: Number of guard subcarriers	10
N_{ST}: Total number of used subcarriers	118 (= N_{SD}+N_{SP}+N_{SG})
Δ_{F}: Subcarrier frequency spacing	4.125 MHz (= 528MHz/128)
T_{FFT}: IFFT/FFT period	242.4 ns (1/Δ_{F})
T_{ZP}: Zero Padding duration	70.08 ns
T_{SYM}: Symbol interval	312.5 ns (= T_{FFT}+T_{ZP})
L_c: Spreading sequence lengths	$1, 4, 8, 16, 32, 64$

$$\Pi(t) = \begin{cases} 1 & 0 \leqslant t \leqslant T_{\mathrm{FFT}} \\ 0 & T_{\mathrm{FFT}} \leqslant t \leqslant T_{\mathrm{FFT}} + T_{\mathrm{ZP}}. \end{cases} \quad (2)$$

$C_l = [c_{l,1} \ldots c_{l,m} \ldots c_{l,L}]$ is the l^{th} Walsh-Hadamard orthogonal spreading code and $D_l(i)$ represents the P complex symbols, belonging to a QPSK constellation and which are transmitted by a block of L_c subcarriers considered during the OFDM symbol i. P then represents the load, and is namely equal to L_c in the full load case and to $L_c/2$ in the half load case. m denotes a chip of the l^{th} spreading code and is varying from 1 to L_c, with $m = n$ mod(L_c).

The MMSE detection coefficients used to compensate for the channel effects write:

$$g_{n,i} = \frac{h^*_{n,i}}{|h_{n,i}|^2 + \frac{1}{\gamma_{n,i}}} \quad (3)$$

where $h_{n,i}$ and $\gamma_{n,i}$ represent the complex channel response and the signal to noise ratio for subcarrier n of symbol i, respectively.

C. SS-MC-MA advantages

Let us consider the case of the SS-MC-MA system working in the mode 1 of the MBOA standard (Fig. 1) as it is proposed in most of the studies.

1) Case of three or less users: The SS-MC-MA system allows the allocation of a 528 MHz sub-band for each user. This system offers the same performance and advantages as MC-CDMA, but needs a more simple channel estimation process in reception. In fact, with SS-MC-MA a given subcarrier is distorted by only one channel, the one of the user associated with this subcarrier. At the contrary, with an MC-CDMA system, each subcarrier is corrupted by different channels of different users, which increases considerably channel estimation complexity. In that case, each user has to estimate the response of many channels all over the total available bandwidth.

2) Case of more than three users: The code dimension could be exploited in SS-MC-MA to share a same 528 MHz sub-band between 2 or even 3 users if necessary. In that case, the generated signal within a given block corresponds to an MC-CDMA signal, but with a limited number of users per block (2 or even 3). Thus, it is possible to have 6 or more users in the first mode with SS-MC-MA compared to the MBOA solution for which conflicts appear from 4 users.

More generally, in a multi-piconet context, the possibility of easily modifying the number of spreading codes assigned to a given user in a given piconet, allows the SS-MC-MA scheme to offer a more flexible and efficient dynamic resource sharing than the MBOA solution does.

IV. SPREADING COMPONENT HANDLING

A. Spreading block assignment strategy

In SS-MC-MA systems, two different frequency allocation schemes can actually be considered to form the spreading blocks.

The first frequency allocation scheme is a "the standard block interleaving scheme" which consists in interleaving the subcarriers assigned to one user so that the chips of the spread symbol belonging to that user are regularly distributed across the whole bandwidth. Thus, maximum frequency diversity is made available at the receiver.

The second scheme is called "adjacent subcarrier scheme" as it gathers the chips of one user's spread symbol on neighboring subcarriers. In contrast to the first scheme, the adjacent subcarrier scheme provides a weaker exploitation of the available frequency diversity. However, the correlation between channel coefficients of adjacent subcarriers is more important, and consequently the channel variance σ_h^2 is smaller. It is explained in [6] that the variance of the SI σ_{SI}^2 is proportional to σ_h^2 over a specific subset of subcarriers. So, by using adjacent subcarriers, the channel variance is limited and so is the SI.

In this paper, the "adjacent subcarrier scheme" has been chosen in order to limit the SI. In this case, the frequency diversity is jointly exploited by the spreading component and the channel coding combined with binary interleaving.

B. Optimization of the spreading code length

The spreading code length L_c has a direct influence on the SS-MC-MA system performance. The longer the spreading codes are, the more the system takes advantage of the frequency diversity. Moreover, the system flexibility increases with L_c by the possibility to obtain a broad choice of data rates. However, the subcarriers of one spreading block undergo a stronger distortion due to the channel selectivity, which induces an increase of the SI. Using shorter spreading codes length reduces the SI to the detriment of a weaker channel diversity exploitation. In that case, for low coding rates, the channel decoder is expected to compensate for the diversity loss. In other words, the channel coding combined with binary interleaving should allow to recover the frequency diversity. At the contrary, for high coding rates, i.e. for coding rates R that tend to 1, the system tends to a non-coded system, so the using of longer spreading code may be preferable in order to collect enough diversity.

C. Selection of the spreading codes

In presence of multipath channels, the orthogonality between spreading sequences is broken and not completely restored by the MMSE detector, then a residual SI term remains. The analytic expression of the SI power associated to the data j for the case of a synchronous SS-MC-MA transmission is given by:

$$\sigma_{SI,j}^2 = \underbrace{(P-1)R_j(0)L_c}_{\alpha} + \sum_{\substack{m=1\\m\neq j}}^{P} \left\{ \begin{array}{c} 2R_j(1)\underbrace{\sum_{n=1}^{L_c-1} w_n^{(j,m)} w_{n+1}^{(j,m)}}_{\beta_{j,m}} + \\ 2R_j(2)\underbrace{\sum_{n=1}^{L_c-2} w_n^{(j,m)} w_{n+2}^{(j,m)}}_{\gamma_{j,m}} + \ldots \\ 2R_j(L_c-1) w_1^{(j,m)} w_{L_c}^{(j,m)} \end{array} \right\} \quad (4)$$

where R_j is the autocorrelation defined as $R_j(p-q) = E[a_{p,j}.a_{q,j}]$. $a_{n,j} = h_{n,j}.g_{n,j}$ is the coefficient affecting subcarrier n after equalization, with $h_{n,j}$ and $g_{n,j}$ the channel and equalization coefficients respectively. $w_n^{j,m} = c_{n,j}.c_{n,m}$ represents the product between the chip elements of the spreading sequences used by data j and m at the subcarrier n, and $P \leqslant L_c$ is the number of active codes.

An optimized spreading code assignment is proposed in [7] to minimize the SI. Judicious subsets of P spreading sequences, whose minimal number of transitions $(+1/-1)$ among each possible product vector $W^{(j,m)} = (w_1^{(j,m)}, w_2^{(j,m)}, \ldots, w_{L_c}^{(j,m)})$ is maximum, are selected. Indeed, each product vector $W^{(j,m)}$ can have between 0 and $L_c - 1$ transitions. Then, depending on the set of selected spreading sequences, the set of corresponding product vectors has a given minimum which can be different from the minimum of another set. The selected spreading sequences subset is the one whose minimum vectors product is maximal compare to the minimum of the other subsets. In this case, the sum over m of negative terms $\beta_{j,m}$ in (4) decreases, which reduces the SI due to large positive value α. $W^{(j,m)}$ has to be understood, here, as a measure of the ability to reduce interference between data j and m. With this criterion, the largest degradation among two symbols could be minimized.

V. System Performance

This section presents results obtained with different spreading code lengths L_c and the performance of the SS-MC-MA system for a given L_c.

A. UWB channel modeling

The channel model used is the one adopted by the IEEE 802.15.3a channel modeling sub-committee for the evaluation of UWB physical layer proposals [8]. This model results from Saleh-Valenzuela model for indoor application [9]. This ray based model takes into account clusters phenomena highlighted during channel measurements. Mathematically, the impulse response of the multipath model is given by:

$$h_k(t) = X_k \sum_{z=0}^{Z_k} \sum_{b=0}^{B_k} \alpha_k(z,b)\delta\left(t - T_k(z) - \tau_k(z,b)\right) \quad (5)$$

where X_k is the log-normal shadowing of the k^{th} channel realization, $T_k(z)$ is the delay of cluster z, and $\alpha_k(z,b)$ and $\tau_k(z,b)$ represent the gain and the delay of multipath b within cluster z respectively. The mean excess delay τ_m and the root mean square delay spread τ_{rms} for the 4 channel models CMi are presented in detail in [8].

Frames of 150 OFDM symbols are used in simulations, and one different channel realization is applied on each new frame. The 100 different realizations are used for each CMi. In this paper, performances are estimated for UWB channel model CM1 which is in Line Of Sight (LOS) configuration.

B. The spreading code length effects

The objective is to find the best compromise between the spreading code length L_c and the coding rate R. So, we present the system performance obtained versus L_c: for a given R and a given load P. Optimized SS-MC-MA systems are simulated for a given E_b/N_0. Three coding rates $R = [1/3, 1/2, 3/4]$ and three loads $P = [L_c/4, L_c/2, L_c]$ are considered.

Results are exhibited for channel CM1 in Fig. 4. They show that L_c and R have a strong influence on the SS-MC-MA

TABLE II
POSSIBLE DATA RATES WITH SS-MC-MA

Data rate (Mbit/s)	**Modulation**	**Coding rate (*R*)**	$\mathbf{L_c}$	**Load (*P*)**	**Coded bit per symbol**
51.2	QPSK	1/3	16	4	48
76.7	QPSK	1/3	16	6	72
115.1	QPSK	1/3	16	9	108
153.6	QPSK	1/3	16	12	144
192	QPSK	1/2	16	10	120
307	QPSK	1/2	16	16	192
409	QPSK	2/3	16	16	192
460	QPSK	3/4	16	16	192

system performance. For low coding rates, the curves tendency shows that it is better to use short code lengths (Fig. 4(a)) and reciprocally, that the more the coding rate is increased, the longer the code length should be (Fig. 4(b) and Fig. 4(c)).

Indeed, the use of short spreading code lengths allows to minimize the SI and, combined with a low coding rate, it allows to benefit from the channel diversity. At the contrary, when the coding rates increase, the decoder is less able to exploit the channel diversity and longer spreading codes are necessary to compensate for this weakness. Note that for high coding rates, the system tends to a non-coded system. So, the observed behavior is consistent with the conclusions already drawn in [10] which shows that the performance of the SS-MC-MA system without channel coding are optimal with L_c set to its maximal value to benefit from the maximum of diversity.

C. Performance of the SS-MC-MA system with $L_c = 16$

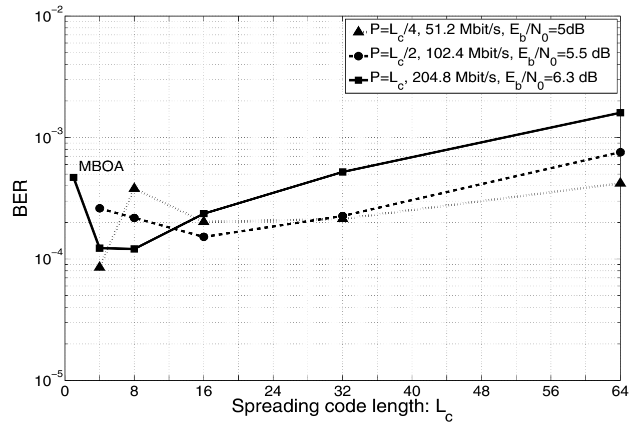
In Fig. 5, $L_c = 16$ was chosen to assess the performance of the SS-MC-MA system since it seems to be a good compromise for the coding rates used, according to the previous results. The joint assignment of the number P of spreading codes and the coding rate R provides different data rates. Table II introduces the code number/coding rate pairs that lead to SS-MC-MA data rates values that are very close of the ones of the MBOA solution. Fig. 5 exhibits the results obtained in the ideal case of perfect channel estimation for the data rates of Table II.

Compared to MBOA, the gain in term of required E_b/N_0 to obtain a BER equal to 10^{-4} with SS-MC-MA on channel CM1 varies from 0.5 to 1 dB. The best gain is obtained for low coding rate, while the performances of the two systems tend to be close when R tends to one.

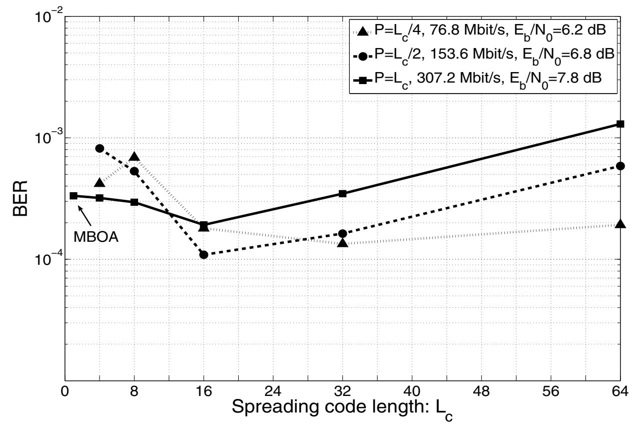
VI. CONCLUSION

In this paper we have presented some methods to optimize the performance of an UWB system based on the SS-MC-MA waveform. In particular, we have selected an adjacent subcarrier scheme and introduced a code selection approach to reduce the SI. In addition, the spreading code length effects have been studied versus the coding rate in order to find the best compromise to exploit at best the channel diversity without degrading the performance by introducing too much SI. We can conclude that an optimal working of the SS-MC-MA system consists in increasing the spreading factor when the coding rate is getting higher.

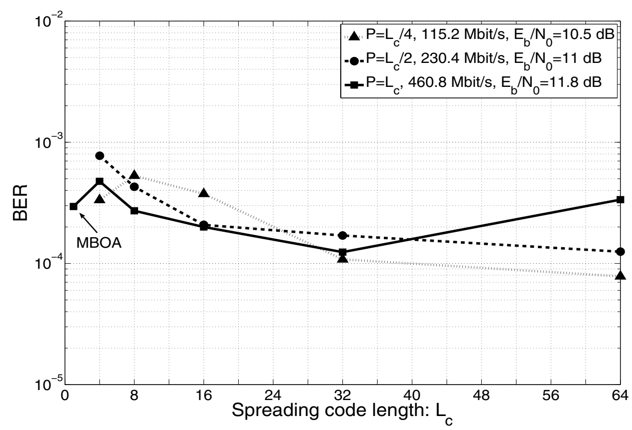
To complete these results, we have plotted the performance of the SS-MC-MA system for a given spreading code length. We have hereby shown that the optimized new system outper-



(a) Coding rate $R = 1/3$



(b) Coding rate $R = 1/2$



(c) Coding rate $R = 3/4$

Fig. 4. SS-MC-MA system performance versus the spreading code length L_c for channel model CM1.

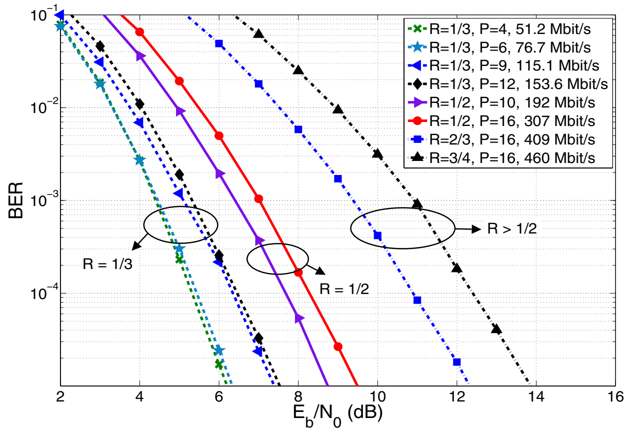


Fig. 5. Performance of the SS-MC-MA system for channel model CM1.

forms MBOA, which tends to prove that the new waveform is more adapted to face frequency selectivity. Eventually, we have improved the MBOA system by simply adding an Hadamard transformation function.

Acknowledgment

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